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The effect of soil physical amendments on reclamation of a saline sodic soil: simulation of salt leaching using HYDRUS-1D

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Running title: HYDRUS can simulate salt leaching in soil profiles

Abstract

Poor soil physical conditions such as low hydraulic conductivity can limit salt depletion from surface soil. Altering the pore system by addition of organic and inorganic amendments may improve salt leaching as a reclamation strategy. Column studies were conducted to investigate salt leaching in amended and non-amended soil profiles. A one-dimensional water and solute transport model (HYDRUS-1D) was also assessed for its applicability to simulate salt leaching for amendment strategy. Columns of a length of 300 mm were filled with saline-sodic soil at the lower end (100-300 mm) and then covered with soil amended with 40% (wt/wt) fine sand and 20% (wt/wt) wood chips, separately. A control column was filled with saline-sodic soil only. One rainfall scenario typical for a location in South-West Queensland (Australia) was applied to the columns. Water potentials were monitored using tensiometers installed at three depths (35, 120 and 250 mm). The concentrations of individual cations (Na^+ , Ca^{2+} , Mg^{2+} and K^+), electrical conductivity and sodium adsorption ratio of the soil solutions were also monitored for the investigated depths. A reduction in surface salinity (up to 28.5%) was observed in the amended soil profiles. This study indicates that the addition of wood chips to surface soil improves salt leaching under the tested conditions. The simulation successfully predicted both hydrology and chemistry of the columns. This study also concluded that HYDRUS-1D is a powerful tool to simulate salt leaching in the amended soil profiles, and can be applied to predict the success of amendment strategy under natural climatic conditions.

Key words: fine sand, HYDRUS-1D, salt leaching, soil amendments, wood chips

Introduction

Land use activities such as mining (Merrill *et al.* 1990), oil and gas extraction (Kharaka and Otton 2007) as well as agricultural activities (Bennett *et al.* 2009) can result in secondary salinization of soil. Rehabilitation of these salt affected soils appears necessary as salt affected soils can be (re-)used for agricultural purposes such as production of fodder (Debez *et al.* 2011). Salt leaching plays a crucial role in the reclamation of salt affected soils since it reduces salt concentrations in the surface soil and provides conditions for plant establishment (Qadir *et al.* 2000). However, soils with low hydraulic conductivity can limit downward water movement to provide adequate leaching (Shaw and Thorburn 1985; Harker and Mikalson 1990; Hoffman and Shannon 2007; Shaygan *et al.* 2017b). Saline-sodic soils typically show poor soil physical conditions which are associated with low hydraulic conductivity, infiltration and drainage (Shainberg and Letey 1984; Rengasamy and Olsson 1991; So and Aylmore 1993; Ben-Hur *et al.* 2009; Reading *et al.* 2012b; Shaygan *et al.* 2017b) that can affect the success of land reclamation and revegetation (Belden *et al.* 1990). Therefore, some remediation strategies are required to improve soil physical condition to enhance salt leaching and create more favourable conditions for establishing plants.

Reclamation of saline-sodic soil is typically performed by application of calcium (Ca) amendments to improve the soil pore system and facilitate salt leaching (Jury *et al.* 1979; Qadir *et al.* 1996). The typical source of Ca for land reclamation is gypsum (Jury *et al.* 1979; Rengasamy and Olsson 1991; Sumner 1993; Qadir *et al.* 1996). However, when gypsum naturally exists in the soil, application of gypsum increases salinity and limits plant establishment (Schuman *et al.* 1989; Belden *et al.* 1990). In addition, the application of chemical amendments and their subsequent drainage may have adverse effects on the environment (Qadir and Oster 2004; Qadir *et al.* 2006). Therefore, reclamation strategies need to be specific to the site and context.

The improvement in soil physical conditions (i.e. pore size distribution and continuity) through amendments can enhance salt leaching (Lax *et al.* 1994; Badia 2000; Tejada *et al.* 2006; Li and Keren 2009; Shaygan *et al.* 2017b). For example, salt leaching improves when organic materials such as manure (Wahid *et al.* 1998; Jalali and Ranjbar 2009; Yazdanpanah and Mahmoodabadi 2011) and compost (Avnimelech *et al.* 1994; Tejada *et al.* 2006; Chaganti *et al.* 2015) are applied to soil. Yet, the literature still lacks of information about the effect of physical amendments (i.e. fine sand and plant residue) on salt leaching.

Salt movement within soil profiles are also affected by climatic conditions as well as soil characteristics (Duan *et al.* 2011). This is particularly important for the reclamation of land in arid and semi-arid environments with highly variable rainfall patterns, where an extended period of dry conditions can result in the upward movement of water and salt to the surface soil (Keyes *et al.* 1999). Therefore, soil-climate interactions and their effect on salt movement (e.g., salt distribution and salt precipitation) have to be considered for the evaluation of salt leaching success and long-term soil reclamation.

Numerical modelling is a meaningful tool to assess and predict the effect of long-term climatic conditions on water movement and salt leaching (Rasouli *et al.* 2013). Salt leaching is controlled by factors such as evaporation and rainfall rates, salt precipitation, soil mineralogy, soil cation exchange and changes in soil chemistry, the effect of soil chemistry on soil physical properties (water movement) and the interrelations of all mentioned factors. Field studies on salt leaching are usually based only on relatively simple functional relationships and cannot completely cover the spatial and temporal variability at the field scale (Gonçalves *et al.* 2006; Rasouli *et al.* 2013). On the other hand, numerical models can perform complex scenarios and integrate empirical (observed) climatic conditions and soil factors (soil chemical and physical properties as well as soil hydrology).

The evaluation of salt leaching requires a numerical model that can simulate water and solute transport and enumerate cation exchange, mineral dissolution and precipitation and changes in soil hydraulic conductivity in relation to the modification of the soil chemistry (Šimůnek and Suarez 1997; Gonçalves et al. 2006; Reading *et al.* 2012a). A number of models can be used to simulate and predict solute transport in soil profiles such as LEACHM (Hutson and Wagenet 1989), UNSATCHEM (Šimůnek and Suarez 1994) or HYDRUS (Šimůnek *et al.* 2008). UNSATCHEM and HYDRUS are currently the only models able to account for the effect of soil chemistry on hydraulic conductivity (Reading *et al.* 2012a) – critical for the assessment of land reclamation plans. Furthermore, the major ion chemistry and carbon dioxide modules of UNSATCHEM are incorporated in the HYDRUS-1D package (Šimůnek *et al.* 2008), making HYDRUS-1D a powerful tool for assessing water and solute transport across one-dimensional soil profiles. Yet, HYDRUS-1D has not been used to assess amendment strategy for salt leaching and soil reclamation.

The aims of this study are (i) to investigate the effect of soil physical amendments on salt leaching from surface soil to create a better condition for halophytes establishment, and (ii) to investigate the applicability of HYDRUS-1D to predict salt leaching in the context of soil amendment strategy.

Materials and Methods

Study site

Saline-sodic soil was collected from a site affected by secondary salinization in north of Eromanga, South-West Queensland, Australia (26°27'05.12" S, 143°25'43.77" E). The study site was part of alluvial plain with low gradient area with low energy flow and no pebbles. The investigated soil (18% clay, 60% silt, 22% sand; silty loam) was affected by saline water, which was a by-product of oil extraction, stored in a series of evaporation ponds. The extraction of oil from reservoirs is accompanied by brine. As a consequence of ongoing

leakage from these evaporation ponds, the salinity and sodicity of the surrounding soil (30 ha) were elevated. This resulted in the death of most plant species around the evaporation ponds and existence of very sparse vegetation cover (halophytes). The soil that surrounded the ponds was classified as saline-sodic based on Australian soil classification (Northcote and Skene 1972). The soil was also non-calcareous, and X-Ray Diffraction analysis indicated that the soil naturally contained gypsum (17% wt). Gypsum can affect cation exchange and leaching characteristics thus it can influence solute transport and leaching behaviour of salts from the soil (Shaygan *et al.* 2017b).

The oilfield brine was saline (EC= ~ 4dS/m), sodium bicarbonate dominated and alkaline (pH varied between 7.9 and 9.2) (Fletcher *et al.* 2009; Shaygan *et al.* 2018). The brine also contained high levels of Boron (1-7 ppm) and Fluorine (4-40 ppm) (Fletcher *et al.* 2009; Shaygan *et al.* 2018). The groundwater was highly saline (EC 54-72 dS/m), sodium chloride dominated and acidic (pH 3.1 to 5) (Shaygan *et al.* 2018). Groundwater included F <0.1 ppm and B <1 ppm (Shaygan *et al.* 2018). The depth of groundwater to the soil surface was between 460 mm and 1040 mm in the vicinity of evaporation ponds (Shaygan *et al.* 2018). The level of hydrocarbons in the groundwater and local soil was insignificant (Shaygan *et al.* 2018). There were no significant differences in the salinity of the soil from the depth of 200 mm to 1000 mm (Shaygan *et al.* 2018). The soil around the evaporation ponds was moist because of the presence of a shallow groundwater level, silty nature of the soil and high evaporation (Baumgartl and Richards 2012; Shaygan *et al.* 2018). The average hydraulic conductivity of the bare soil in the depth of 40-80 mm ($n=48$) was 1.41×10^{-7} m/s (Shaygan *et al.* 2018).

In Australia, the brine affected soil requires rehabilitation to meet legislative guidelines. The reclamation plan for this site is to improve soil physical properties (e.g. macro-pores, hydraulic conductivity) using physical amendments for facilitating salt leaching and thus

creating a better condition for establishing salt tolerant plants (halophytes), which can be used as a fodder for livestock. Based on the preceding studies on the site (Fletcher *et al.* 2009; Shaygan *et al.* 2018), the following series of laboratory studies were conducted to investigate the effect of physical amendments on salt leaching from surface soil (0-50 mm) under controlled conditions. Such laboratory studies are important prior to the investigation of complex scenarios under field conditions, where several climate factors affect salt leaching. Here, we also examined HYDRUS-1D model for its applicability to simulate and predict salt leaching in the soil profiles. We focused more on surface soil (0-50 mm) as this soil layer supports seed germination and early stages of plant establishment (Shaygan 2016).

Determining physical and chemical properties of soil substrates

The soil of the site was collected to a depth of 200 mm because a previous study (Shaygan *et al.* 2018) showed no significant differences between chemical properties of the soil at the depth of 200 mm and deeper depths of the soil profile. . The collected soil was dried at 35 °C and sieved to pass 2 mm. The soil used in this study represents the soil texture of the surface horizon, and sieving soil through 2 mm is the best way to prepare the soil columns. The sieved soil (<2 mm) was mixed with 20% (wt/wt) red gum tree wood chips (<2 mm; EC: 0.55 dS/m; pH: 4.37), which contained 2.7 g/kg Ca, 0.5 g/kg Na, 0.4 g/kg Mg, 0.6 g/kg K, and 40% (wt/wt) washed fine sand (~100-300 µm; EC: 0.08 dS/m; pH: 7.48), separately. These soil amendments are available in Australian market and accessible to the site. The small size of wood chips (<2 mm) was used due to the small size of the column studies. Fine sand was used in this study as previous studies on the site indicated that there is a significant difference between the fine sand content in vegetated and bare areas (Shaygan *et al.* 2018). Furthermore, addition of coarse sand can reduce water holding capacity of the soil and plant available water. We did not use gypsum as an amendment for this study as the soil contains gypsum and addition of gypsum increases the soil salinity and further limit plant

establishment (Schuman *et al.* 1989; Belden *et al.* 1990). The rate of the amendments used in this study was selected based on preceding studies which showed soil amended with 40% fine sand and 20% wood chips had a higher hydraulic conductivity value than that of the non-amended soil (Shaygan *et al.* 2017b). The selected rates of the amendments were also used in other studies such as revegetation of mine spoil (Belden *et al.* 1990) and tailings (Huang *et al.* 2011) under (semi)arid climatic conditions for the purpose of improving salt leaching to create a condition for plant establishment. The amendments mixed with the soil using shaker (Gerhardt Rotoshake; Gerhardt, Cologne, Germany) for eight h followed the method described in Shaygan *et al.* (2017b). The basic chemical and physical properties of the amended and non-amended soils are summarised in Tables 1-4.

The exchangeable cations of the amended and non-amended soil were measured after pre-treatment to remove soluble salts (Rayment and Lyons 2011). The soil samples were pre-treated and leached sequentially with 60% aqueous ethanol and 20% aqueous glycerol by adding 25 mL of leaching solution to 5 g of soil sample and shaking for 30 min (Rayment and Lyons 2011). The exchangeable cations (Na^+ , K^+ , Ca^{2+} , Mg^{2+}) then were released using a 1:20 w/v (soil: 1 M NH_4Cl) extraction (Rayment and Lyons 2011) and analysed by a Varian Vista-Pro inductively-coupled plasma-optical emission spectrometer (ICP-OES).

For measuring the soil physical properties, the amended and non-amended soils were packed in small cylinders (40 mm height and 56 mm diameter) and compacted under controlled conditions to achieve bulk density of $1.20 \pm 0.02 \text{ g/cm}^3$. The bulk density of the columns filled with 20% wood chips amended soil was approximately $0.9 \pm 0.02 \text{ g/cm}^3$ due to the low particle density of the wood chips. The bulk density of 1.2 g/cm^3 and 0.9 g/cm^3 have been chosen based on the range of bulk densities under vegetated areas of the site (Shaygan *et al.* 2018). After packing the soils into the small cylinders, the soil cores were used for estimating soil hydraulic conductivity and water retention curve parameters. The saturated hydraulic

conductivity of the soil substrates was measured using a constant head permeability test (Klute and Dirksen 1982). In this study, DI-water was applied to the columns from the bottom of the soil cores, while the flow rate and hydraulic conductivity were determined based on the volume of water passing through the soil cores (Darcy's law) (Marshall, et al. 1996) upon stabilisation of the flow rate (Reading et al. 2015). Saturated hydraulic conductivity is typically measured once an "apparent steady state" is reached since chemical or physical changes (i.e., cation exchange, clay swelling, dispersion or mobilization) can occur in the soil while it is leached (Quirk and Schofield 1955; McNeal and Coleman 1966). The water retention curve parameters were determined by the desiccation of water saturated soil cores to -1, -2 and -3 kPa for 24 h each using a sand based tension table. Vacuum controlled pressure was used to achieve a lower water suction; the soil cores were placed on a porous plate for 4 days, 6 days and 5 days, sequentially to obtain water content at -10, -30 and -50 kPa. Following the last desiccation step, samples (soil cores) were dried at 105°C in the drying oven for 24 h to determine the bulk density. Drying samples for 24 h was sufficient since the soil had low clay content, and soil cores were small. The soil samples were weighed to determine the gravimetric water content for each desiccation step. The volumetric water content of each treatment was calculated after measuring the gravimetric water content by multiplication with the sample bulk density. Two subsamples were prepared by a small ring (9 mm height and 18 mm diameter) for each treatment to determine the water content for the desiccation at equivalent -500 kPa using a pressure plate extractor (1500F1; Soil Moisture, Santa Barbara, USA) for 3 weeks. As the pressure plate could not provide any pressure more than -500 kPa, subsamples were used to determine water content for the desiccation at -500 kPa. The subsamples were weighed to determine the gravimetric water content. Then the volumetric water content of each treatment at -500 kPa was calculated after measuring the gravimetric water content by multiplication with the bulk

density of the sample (large soil cores). The water retention curve of each soil substrate was determined based on the measured data at -1, -2, -3, -10, -30, -50 and -500 kPa. The pore size classes were determined based on the values for field capacity and permanent wilting point as described in Shaygan et al. (2017b). The parameters of α and n were estimated using RETC (van Genuchten *et al.* 1991). For the fitting procedure the residual water content (θ_r) was set to zero. The macro-pore volume was also determined based on the values for saturation and field capacity (Shaygan *et al.* 2017b).

Laboratory column study

After measuring physical and chemical properties of the soil substrates, a series of laboratory column studies were conducted to evaluate the water and solute transport within the soil profiles. To evaluate water movement within the soil profiles, the saline-sodic soil was packed into 300 mm long (height) columns (70 mm diameter) from a depth of 100 to 300 mm and then covered with the soil mixed with 40% (wt/wt) fine sand and 20% (wt/wt) wood chips, separately (Fig. 1). As a control, a column filled with saline-sodic soil and no amendments was used (Fig. 1). The 300 mm long columns were chosen for this study to replicate the field conditions in the vicinity of the evaporation ponds. The columns were filled to achieve a bulk density of 1.2 g/cm³. The bulk density of the wood chips amended soil was 0.9 g/cm³. After packing, the columns were subjected to three wet-dry cycles to achieve consolidation after refilling without leaching. The columns were moistened by DI-water from the bottom of the columns for 24 h and then allowed to dry for 7 days in a 35 °C oven. Following the last cycle, the columns were saturated with DI-water.

To evaluate water movement within the soil profiles, the experiments were carried out by establishing an initial water potential of -6 kPa at the soil surface through lowering the bottom outflow tube to 300 mm below the lower end of the column and collecting outflow leachate solutions until no outflow occurred (Fig. 1). Then the columns were exposed to

atmospheric laboratory conditions (air). The potential evaporation of the laboratory environment ranged between 0.57 and 1.2 mm/day. We measured the amount of evaporation in the laboratory environment by using a small dish filled with water, and we measured the amount of water loss every day at the same time of day. The temperature of the environment varied between 21 and 24 °C. The hydrological response in the columns was monitored by measuring the soil water potential using tensiometers (T5x; UMS, Munich, Germany) which were installed at three depths (35, 120 and 250 mm) by hand. The water potentials were measured at one-minute intervals. In this study, we refer to matric potential when expressing soil water potential.

A design rainfall of 10.9 mm depth and 10 min duration with an annual exceedance probability of 50% (Bureau of Meteorology, 2014) based on the nearest weather station (Quilpie Airport; 045015) to the site was applied to the soil columns. This specific location was selected for the study as it represents a typical semi-arid Australian environment. The rainfall scenario was applied to the soil columns through spraying of water (Ca^{2+} : 0.024 mmol/L, Na^{+} : 0.043 mmol/L, Mg^{2+} : 0.0411 mmol/L, K^{+} : 0.048 mmol/L, SO_4^{2-} : 0.00157 mmol/L, Cl^{-} : 0.006 mmol/L) uniformly over the soil surface for 10 minutes using a spray-nozzle (Canyon CHS-3AN) of 0.4 mm in diameter. Prior to the experiment, a separate trial was set up to examine that the water can be applied uniformly to the soil surface by spraying. This trial indicated that the water application was uniform, and water application did not disturb the soil surface conditions. After the rain event, the tested soil columns were drained and allowed to dry. The experiments were terminated when the soil water potentials at the depth of 35 mm reached values between -5.6 and -6.1 kPa (approximately initial soil potential before applying rainfall). The experiments were replicated three times using similar columns (Table 5 and Appendix A-B).

To evaluate solute movement within the soil profiles, pore solution was sampled in a separate series of columns following the intent not to influence the water potential in the columns equipped with tensiometers by applying locally negative pressure to extract the soil solution. The initial water potential of -6 kPa at the soil surface was established by lowering the outflow tube to 300 mm below the lower end of the column and exposing the columns to air. Drying through evaporation resulted in upward movement of pore water and salt precipitation similar to field conditions. Soil moisture samplers (Rhizon Flex; Rhizosphere Research Products, Wageningen, the Netherlands) were installed at three depths (35, 120 and 250 mm) by hand to collect the soil solutions after each rainfall application. The suction for soil solution extraction was created using a vacuum pressure (ecoTech; Bonn, Germany) set between -9.5 and -11.0 kPa for wood chips amended columns. For all other columns the pressure was set between -14.0 and -15.0 kPa. The soil solutions were collected during the first 30 minutes for the amended columns and the first 120 minutes for non-amended columns since no outflow was observed after this time period. The solute transport experiments were repeated three times using similar columns (Table 6 and Appendix D-E). [The water movement and solute transport experiments were conducted between November 2014 and March 2015.](#)

The electrical conductivity (EC) of the soil solutions were analysed using TPS-901C EC meter (TPS Pty Ltd; Brisbane; Australia). The concentration of cations (Na^+ , K^+ , Ca^{2+} , Mg^{2+}) were determined using ICP-OES. The concentration of anions (Cl^- and SO_4^{2-}) were determined using IC (Ion Chromatography). The sodium adsorption ratio was calculated using the following equation (Robbins 1984):

$$SAR = \frac{Na^+}{\sqrt{\frac{(Ca^{2+} + Mg^{2+})}{2}}} \quad [1]$$

where Na^+ , Ca^{2+} and Mg^{2+} are the cation concentrations in $\text{mmol}_{(c)} \text{L}^{-1}$ (millimol of charge per litre is an SI unit corresponding to milliequivalent per litre).

Validation of HYDRUS-1D model

In this study, water and solute transport on a laboratory scale was simulated using HYDRUS-1D (version 4.16.0110), with the major ion chemistry module (Šimůnek *et al.* 2008). The results from laboratory column studies were used for comparison with HYDRUS-1D modelling results. In this study, the term ‘validation’ is defined as the process of investigating the accuracy of the model for being representative of the soil systems. The term ‘sensitivity analysis’ is defined as the process of evaluating the accuracy of the model (confidence in model) when input data changes. The components of the HYDRUS-1D model which are applicable for this study are described comprehensively in Šimůnek *et al.* (2008) and Šimůnek *et al.* (2013). The form of the one-dimensional Richards equation that is solved in HYDRUS-1D by the Galerkin-type linear finite element scheme assumes that the air phase plays an insignificant role in the liquid flow process and that water flow due to thermal gradients can be neglected (Šimůnek *et al.* 2013). The single porosity van Genuchten-Mualem model was used in this study because the measured water retention data of the soil substrates did not show dual porosity. The water retention curve permeates of the soil substrates (Table 1) were measured using small soil cores (40 mm height and 56 mm diameter) as mentioned previously. Since soil packing/compaction into a bigger column (300 mm height and 70 mm diameter) can change the soil water retention curve (hydraulic) parameters (Assouline *et al.* 1997; Zhang *et al.* 2006), for HYDRUS modelling the soil water retention curve parameters (α and n) were optimized (Appendix E) by solving the inverse problem (Šimůnek *et al.* 1998; Hopmans *et al.* 2002) using the HYDRUS-1D code (Šimůnek *et al.* 2013). Then, α and n were further optimized by fine tuning as described in Šimůnek and de Vos (1999). Thus, the measured saturated and residual water content together with optimized α and n parameters were used for HYDRUS-1D modelling (Table 2-4).

At the end of the laboratory column study, the columns were dismantled and samples were collected for measuring bulk density. The effect of soil packing/compaction on increasing bulk density at the lower end of the columns was observed. Therefore, a lower saturated hydraulic conductivity of 0.003 cm/min was used in the model for the lower 50 mm of the column based on the inverse modelling results. Jacques *et al.* (2002) also confirmed that the lower hydraulic conductivity is required for the calibration of water and solute transport in deeper depths of the soil profiles. To simulate water movement, an atmospheric boundary condition with no surface run-off and a constant pressure head boundary conditions were applied at the top and the bottom of the column model, respectively.

The advective-dispersive chemical transport under transient flow conditions in partially saturated soil (Suarez and Šimůnek 1996; Šimůnek *et al.* 2013) was used in the model. The model's temporal and spatial discretizations were calculated by the Crank-Nicholson Scheme and Galerkin finite element schemes, respectively as described in Saso *et al.* (2012) and Šimůnek *et al.* (2013). The measured Gapon selectivity coefficients describing the partitioning between the solid phase and solution are listed in Tables 2-4. After comparing the solubility product of gypsum K_{sp}^G , the quantity of gypsum (Tables 2-4) was obtained by solving the quadratic equation as Suarez and Šimůnek (1997) described. In HYDRUS, it is assumed that the cation exchange capacity is constant and pH independent, and the cation exchange capacity (CEC) is equal to the sum of the adsorbed concentrations of the four cations (Na^+ , Ca^{2+} , Mg^{2+} and K^+). The initial soil solution concentrations were set up to the measured soluble cations (Na^+ , K^+ , Ca^{2+} , Mg^{2+}) and anions (Cl^- , SO_4^{2-}) of the soil substrates before leaching (Tables 2-4). A small amount of alkalinity was added to the applied solution in the model since it was determined that this improved the stabilities in the chemistry results (Reading *et al.* 2012). The diffusion coefficient value of 0.001 cm²/min (1.62×10^{-5} cm²/s)

was used for the modelling as it was the diffusion coefficient of NaCl (Fell and Hutchison 1971).

To simulate solute transport, the “concentration flux BC” was selected for the upper boundary condition. For the lower boundary condition, the zero gradient boundary condition is the most appropriate to use, particularly when the water flow is directed out of the modelled domain (Šimůnek *et al.* 2013). The “kinetic precipitation/dissolution” function was activated. The initial pressure head of the soil surface was set at -6 kPa, with -3 kPa being set for the lower boundary condition to represent the 300 mm long column. Similar to the laboratory column study, two materials were used for the simulation of the amended columns, and one material was used for the simulation of the non-amended column (control). The sensitivity analysis was used to assess the effect of the initial soil chemistry, cation exchange properties, and solute transport parameters on the salt movement results (Table 2-4). The HYDRUS parameters which were selected for the sensitivity analysis were those probably having the most influence on the solute transport. In the major ion chemistry module of HYDRUS-1D, there is a function that considers the effect of solution chemistry on hydraulic conductivity (Šimůnek *et al.* 2013; Reading *et al.* 2012). The reduction function is based on the study of McNeal (1968) and Suarez *et al.* (1984) which was further discussed in Ezlit *et al.* (2013). The K_{red} function depends on salt concentration of the solution, soil ESP, and the pH of the soil solution (Reading, *et al.*, 2012, Šimůnek, *et al.*, 2008b). This function decreases the hydraulic conductivity when the soil chemistry is below “optimum conditions” to account for the impacts of soil swelling (Reading, *et al.*, 2012, Šimůnek, *et al.*, 2008b). The “optimum conditions” in HYDRUS-1D consider as a low pH, below 6.83, and a high salt concentration, at least 300 meq/L. The simulation was also carried out with and without considering the K_{red} function to indicate the differences in simulated timing for

solute transport with and without consideration of the influence of chemistry on the hydraulic properties.

Statistical Analysis

The soil data was analysed statistically using one-way ANOVA followed by Duncan's test ($P < 0.05$). Five statistical procedures (Appendix F) were used to assess the level of agreement between the predicted and observed data (to validate the model): The root mean square error (RMSE) (Legates and McCabe 1999; Saso *et al.* 2012; Zeng *et al.* 2014), the Nash-Sutcliffe coefficient (NSE) (Nash and Sutcliffe 1970, Zeng *et al.* 2014), the index of agreement (d) (Willmott 1981), and for the solute transport simulations the mean absolute error (MAE) and relative error (RE). The model is more accurate when the RMSE or MAE is close to zero, or the NSE or d approach one. The RE value is used to assess the quality of the RMSE value (Yurtseven *et al.* 2013). The simulation is considered excellent when RE is less than 10% (Loague and Green 1991; Yurtseven *et al.* 2013).

In this study, time series for the simulated water potential equalled the time series for the measured water potentials. For example, we compared 9170, 9948 and 10563 simulated and measured data for each depth of non-amended soil, wood chips amended soil and fine sand amended soil profiles, respectively for the first replicate (Table 4). The number of atmospheric boundary condition (rainfall and evaporation) equalled the time series. For instance, we provided 9170, 9948, 10563 rainfall and evaporation data for the first replicate of water movement simulation (Table 4). For solute transport simulation, time series were 30 for the amended soil columns and 120 for the non-amended soil column. Time series were the same for all solute transport replicates. The number of atmospheric boundary condition (rainfall and evaporation) equalled the time series for each column.

Results

Physical properties of the soil substrates

The hydraulic conductivity was increased ($P<0.05$) to 2.9×10^{-6} and 3.6×10^{-6} m/s when the soil mixed with fine sand and wood chips, respectively (Table 1). Moreover, a higher porosity ($0.68\text{ cm}^3/\text{cm}^3$) and macro-pore volume ($0.22\text{ cm}^3/\text{cm}^3$) were observed in the wood chips amended soil than those of the non-amended soil with $0.56\text{ cm}^3/\text{cm}^3$ porosity and $0.17\text{ cm}^3/\text{cm}^3$ macro-pore volume (Table 1). Soil amended with fine sand had also a higher macro-pore volume ($0.18\text{ cm}^3/\text{cm}^3$) compared with that of the non-amended soil (Table 1).

Distribution of solutes in saline-sodic soil columns

Surface soil salinity is a critical factor affecting seed germination and plant establishment (Shaygan *et al.* 2017a). In this study, the lower ($P<0.05$) salinity was observed in the surface soil solutions of the wood chips amended (11.94 ± 0.16 dS/m) and fine sand amended (12.17 ± 0.14 dS/m) columns compared to that of the non-amended column (16.7 ± 0.25 dS/m) (Table 7). Sodium adsorption ratios were also 23.6% and 6.2% lower in the surface soil of the wood chips amended and fine sand amended columns, respectively, compared to that of the non-amended column (Table 7). Sodium content also reduced ($P<0.05$) in the surface soil of the wood chips amended (102.69 ± 6.52 mmol/L) and fine sand amended (114.01 ± 5.22 mmol/L) columns compared with that of the non-amended column (148.38 ± 0.43 mmol/L) (Table 7). Magnesium concentration was lower ($P<0.05$) in the surface soil solution of the fine sand amended column (Table 7). There were no significant differences among Ca^{2+} concentrations and K^{+} concentrations of surface soil solutions of the studied columns (Table 7). The greater electrical conductivities were observed in the depth of 120 and 250 mm of the soil columns compared with those of the surface soils (Table 8-9). No significant differences were also found for the concentrations of ions at deeper depths of the studied soil columns (Table 8-9). Distribution of Na^{+} , Mg^{2+} and K^{+} concentrations also followed similar pattern to distribution of EC in the investigated soil columns, excluding concentration of K^{+} for the wood chips amended column (Table 7-9).

HYDRUS modelling

The model was applied to predict the dynamics of water potentials in the soil profiles. Prior to the statistical analysis for the agreement between the simulated and observed water potentials, the data was checked for plausibility. The index of agreement (d) ranged between 0.96 and 0.99 for the depth of 35 mm of the investigated columns (Table 5). Simulation also reproduced the dynamics of water potentials with the index of agreement values ranging between 0.91 and 0.99 for subsurface soil layers of the studied columns (Table 5). In addition to the accurate prediction of the dynamics of soil water potentials, the model was applied to reproduce the chemistry of the soil profiles. The simulation underestimated salinity, sodicity and Na content of the soil solutions, excluding the first investigated depth of the non-amended column (Fig. 2-3). The RMSE values for EC ranged between 0.73 and 0.84 dS/m (Table 6). The model also reproduced Na^+ concentrations in the investigated soil columns with RMSE values ranging between 6.09 and 7.61 mmol/L (Table 6). The simulation overestimated Ca^{2+} content for the first investigated depth of the non-amended column (Fig. 3). The RMSE values also varied between 0.99 and 0.19 mmol/L for Ca^{2+} distribution in the investigated columns (Table 6). The RE values were less than 10% for the distribution of cations, salinity and sodicity in all investigated soil columns (Table 6).

The chemistry of the soil solution can affect soil hydraulic conductivity (Ezlit, et al., 2013; McNeal, et al., 1968; Suarez, et al., 1984). The simulations to this point assumed that soil chemistry (solution composition) did not affect hydraulic conductivity. To evaluate the effect of soil chemistry on hydraulic conductivity and hence prediction of concentrations of major ions, we reran the simulation with considering K_{red} function. The application of the K_{red} function improved the correlations between the observed and predicted results for the distribution of Na^+ and Mg^{2+} and salinity in the amended columns (Table 6). However, K_{red} function did not lead to significantly different water potentials (Table 5) or cation

concentration in the soil profiles (Table 6). The other replicates of the column study also indicated similar results for dynamics of water potentials (Appendix A-B) and solutes (Appendix C-D) within the soil profiles.

Discussion

Effect of amendments on soil physical properties

Salinity and sodicity and their consequences can limit plant establishment and hence the land revegetation. Leaching to obtain more favourable conditions for seed germination and plant establishment is an important factor for land reclamation, above all for arid and semi-arid environments. Without leaching, salts accumulate in the surface soil (Hoffman and Shannon 2007) and can limit seed germination and plant establishment. Leaching involves the dissolution of soluble salts in the soil profile, thereby displacing the saline solution by water and subsequently removing salts from the soil (Al-Sibai *et al.* 1997). While sources of Ca (e.g. gypsum) can facilitate the cation exchange during displacement and leaching (Marwan and Rowell 1995; David and Dimitrios 2002), the latter can be limited by low hydraulic conductivities of saline-sodic soils. The objective of this study was to enhance salt leaching from surface soil by addition of soil physical amendments to improve soil physical properties such as hydraulic conductivity and pore system.

In this study, both soil amendments (fine sand and wood chips) increased soil hydraulic conductivity and soil macro-pore volume (Table 1) which resulted in downward movement of water and solute to deeper depths of the soil profile and hence reduction of surface soil salinity (Table 7). Addition of fine sand to the surface soil altered the surface soil texture which created larger volume of macro-pores and possibly increased the connectivity among the pores thereby increased the soil hydraulic conductivity (Table 1) and reduced surface soil salinity (Table 7). Rahman *et al.* (1996) also reported that amending soil with sand

increased soil infiltration, promoted deeper penetration of water and increased the desalinization zone.

Addition of wood chips to the surface soil resulted in an increase in the total porosity, and macro-porosity which enhanced the hydraulic conductivity (Table 1). This was similar to the conclusions of other studies evaluating the effect of plant residues on soil physical properties (Mbagwu 1989; Barzegar *et al.* 2002). Similar to Barzegar *et al.* (2002) study which evaluated the effect of wheat straw on soil physical properties, we concluded that plant residues (here, wood chips) can increase soil porosity, macro-pore volume and hence increase infiltration rate and salt leaching from the surface soil.

Land reclamation using soil amendments

The increase in soil hydraulic conductivity resulted in the reduction of the surface soil salinity (Table 7), which is a critical determinant of seed germination and plant establishment (Reichman *et al.* 2006; Arnold *et al.* 2014). Salt leaching has been reported in other studies on amelioration of saline bentonite mine spoil (Belden *et al.* 1990) or saline soil (Rahman *et al.* 1996) by wood residues and sand. Our study also indicates that the addition of physical amendments (40% fine sand or 20% wood chips) to a depth of 100 mm of the soil profile can reduce surface soil salinity when the soil is exposed to intense rain events (≥ 10.9 mm).

These findings have fundamental implications for land reclamation strategies. The greater reduction in surface salinity and sodicity of wood chips amended column (Table 7) suggests that the addition of wood chips is likely to be more successful technique for the reduction of surface salinity and sodicity and thus land reclamation. Barzegar *et al.* (1997) also reported that the addition of organic amendments such as plant residue appears to be a practical path for improving soil structural stability and decreasing salinity and sodicity. In our study, wood chips provided a better condition for salt leaching by creating a greater soil hydraulic

conductivity (Table 1) and volume of macro-pores (Table 1) and also minimizing upward movement of solutes which was observed by no evidence of salt crust after the soil further dried. This study also suggests that halophytes such as *Atriplex halimus*, which has a high fodder quality, can germinate on the soil amended with wood chips after intense rain events (≥ 10.9 mm) since 32% *Atriplex halimus* seed germination was observed at high saline solution (122 mmol NaCl) (Shaygan *et al.* 2017a). Other halophytes such as *Tecticornia pergranulata* and *Frankenia serpyllifolia* can also germinate on the wood chips amended soil after intense rain events (≥ 10.9 mm). The germination of *Tecticornia pergranulata* was observed (~17%) at 23 g/L NaCl (English *et al.* 2002). A 27% germination was also found for *Frankenia serpyllifolia* at solutions with EC of 38.9 dS/m (Easton and Kleindorfer 2009). Subsequently, it was seen that most halophyte seedlings can tolerate high levels of salinity during their vegetation stages, and they can continue to grow at salinity levels that allowed seeds to germinate (Khan and Ungar 1984; Katembe *et al.* 1998; Tobe *et al.* 2000; Shaygan *et al.* 2017a). For all above reasons, the addition of woodchips to the depth of 100 mm of a saline sodic soil appears an effective land reclamation strategy. Nevertheless, this conclusion requires verification under field conditions, particularly in semi-arid environments with dispersed intense rain events. In semi-arid environments, dispersed intense rainfall events may leach the salts to deeper depths at suitable pore size distribution and pore continuity conditions. Consequently, soil amendments may affect the distribution of solutes in the soil profiles and prevent returning solutes to the surface soil. In this regard, a hydro-geochemical model, HYDRUS-1D, can be employed to test and evaluate the opportunity of amendments to contribute to leaching spatially and temporally at a soil profile scale.

HYDRUS-1D as a predictive tool for evaluating land reclamation success

Using the validated HYDRUS-1D model, and similar to other studies (Gonçalves *et al.* 2006; Zeng *et al.* 2014), the empirical observations of the soil hydrology were simulated

with high accuracy under the rain event and over the entire soil profile (Table 5) indicating the model's capacity to predict dynamics of water potentials and water content. Likewise, the model also provided a very good description of the observed values for EC and SAR (Fig. 2 and Table 6) indicating the capacity to simulate both salinity and sodicity with the applied soil amendments. However, simulated values of EC tended to underestimate the measured values (Fig. 2). This is caused by the existence of ions in the soil solution ignored by the model (McNeal *et al.* 1970) as reported by other studies as well (Gonçalves *et al.* 2006; Ramos *et al.* 2011; Yurtseven *et al.* 2013).

While the simulated Na^+ concentration exceeded the measured concentration, the simulated Ca^{2+} concentration was below observed concentration at 35 mm depth in the non-amended column (Fig. 3), indicating that the Ca-Na exchange rate was slightly higher in the laboratory experiments than in the model simulation. As the cation exchange coefficient is one of the primary factors governing the rate of cation exchange in HYDRUS (Reading *et al.* 2012a; Šimůnek *et al.* 2013), the excellent agreement between the simulated and observed Na^+ and Ca^{2+} concentrations in deeper soil in the control column verified the validity of the Ca-Na coefficient value for the non-amended soil. This indicates that the differences in water flow were associated with the smaller Na^+ concentration and salinity for the surface layer of the non-amended column in the laboratory observation. The slower water movement within the surface layer of the non-amended column in the laboratory experiment than that of the simulation possibly resulted in a greater cation exchange reaction and eventually led to greater salt leaching since the slower water movement conducted a greater accessibility of the exchange surfaces which resulted in a greater salt leaching (Hartmann *et al.* 1998; Reading *et al.* 2012b; Shaygan *et al.* 2017b).

Small RE (relative error) values (Table 6) indicate that solute transport parameters (the model) have been precisely calibrated. Due to an excellent agreement between predicted and

observed Ca^{2+} content ($\text{RE} < 9\%$) in the investigated soil profiles, the simulation is considered successful as Reading, et al. (2012a) suggested that concentrations of Ca^{2+} can be a good indication of simulation success since Ca^{2+} concentrations are influenced by Ca-Na exchange, Ca-Mg exchange as well as Ca-K exchange. The success of HYDRUS-1D for predicting chemistry of soil solutions is further confirmed by excellent agreement ($\text{RE} < 9\%$) between observed and simulated Mg^{2+} and K^+ concentrations in the investigated depths of the soil columns (Fig. 4). Therefore, in agreement with other studies (Gonçalves *et al.* 2006; Corwin *et al.* 2007; Ramos *et al.* 2011; Reading *et al.* 2012; Yurtseven *et al.* 2013; Zeng *et al.* 2014) which reported the effectiveness of HYDRUS-1D for simulating water and solute transport, this study demonstrates HYDRUS-1D is able to accurately reproduce the dynamics of water potentials and solute in amended soils as well as non-amended soil. In this study, HYDRUS-1D also confirmed that the addition of wood chips to surface soil can result in a greater reduction of soil salinity as well as sodicity. Therefore, HYDRUS can be used as a predictive tool for evaluating the success of an amendment strategy under natural climatic conditions prior to upscaling to field conditions.

Simulation of leaching also requires a model that can adequately represent both chemical and physical changes in the soil associated with the amelioration process. Hydraulic conductivity reduction function of HYDRUS-1D simulates the effects of soil chemistry on hydraulic conductivity which is an important factor in prediction of salt leaching. We hypothesised that simulation results improve when K_{red} function is applied. In agreement with Reading *et al.* (2012a), our study indicates that simulation describes a better prediction of soil chemistry when the K_{red} function was activated (Table 6). This suggests that applying the K_{red} function is a reasonable solution to improve the prediction for reclamation examples under long-term climatic conditions.

Conclusions

The application of physical amendments to improve soil permeability assists with leaching salts. This study indicates that the addition of 20% wood chips to the surface soil provides a greater level of desalinisation and desodification through increasing through flow and further reducing evaporation. Therefore, addition of wood chips can be applied as a reclamation strategy for salt affected soils to provide a better condition for seed germination and plant establishment. Management of saline-sodic soils also requires knowledge of many coupled physical-chemical processes affecting soil conditions and cannot be covered by laboratory and field studies. This is particularly important for selection of a successful reclamation scenario under natural climatic conditions. The HYDRUS-1D model helps to generate this knowledge and predict the success of the amendment strategy under natural climatic conditions.

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Fig. 1. Conceptual design of the column study

Fig. 2. Observed and simulated data of salinity (dS/m) and SAR ($\text{mmol}_{\text{(c)}} \text{L}^{-1})^{0.5}$ in the soil columns for (a) the non-amended column (control column), (b) the fine sand amended column and (c) the wood chips amended column

Fig. 3. Observed and simulated data of Ca^{2+} and Na^{+} concentrations (mmol/L) in the soil columns for (a) the non-amended column (control column), (b) the fine sand amended column and (c) the wood chips amended column

Fig. 4. Observed and simulated data of Mg^{2+} and K^{+} concentrations (mmol/L) in the soil columns for (a) the non-amended column (control column), (b) the fine sand amended column and (c) the wood chips amended column

Table 1. The properties of the soil substrates

Θ_r : residual water content; Θ_s : saturated water content; α : inverse of the air entry suction; n : measure of the pore size distribution; K_s : saturated hydraulic conductivity; ESP: Exchangeable Sodium Percentage; $EC_{1:5}$: Electrical Conductivity of 1:5 soil solution extract; $pH_{1:5}$: pH of 1:5 soil solution extract; * Significant at $P<0.05$; *** Significant at $P<0.001$; Within the same column, mean values followed by different letters differ significantly according to Duncan's test ($P<0.05$)

Soil substrates	Θ_r	Θ_s	α	n	Macro-pore volume	Porosity volume	K_s	ESP	$EC_{1:5}$	$pH_{1:5}$
	cm^3/cm^3	cm^3/cm^3	1/cm		cm^3/cm^3	cm^3/cm^3	m/s ($n=3$)	% ($n=3$)	dS/m ($n=3$)	($n=3$)
Fine sand amended soil	0	0.489	0.2	1.221	0.18	0.48	$2.9 \times 10^{-6} \pm 1 \times 10^{-6}$ a	60.07 ± 1.7 a	6.69 ± 0.12 b	7.78 ± 0.16 ab
Wood chips amended soil	0	0.688	0.144	1.178	0.22	0.68	$3.6 \times 10^{-6} \pm 1.4 \times 10^{-6}$ a*	61.78 ± 0.8 a	7.96 ± 0.10 b	7.12 ± 0.05 b
Non-amended soil	0	0.562	0.152	1.157	0.17	0.56	$6.6 \times 10^{-7} \pm 1 \times 10^{-7}$ b	54.84 ± 1.91 b*	13.58 ± 0.26 a***	7.96 ± 0.09 a***

Table 2. The HYDRUS model inputs for fine sand amended soil

Parameter	Value (base case)	Range for sensitivity analyses
Exchangeable cation concentration, $\text{cmol}_c \text{ kg}^{-1}$		
Ca	3.47†	3.30-3.64
Mg	2.98†	2.84-3.12
Na	10.27†	9.76-10.78
K	0.174†	0.16-0.18
Cation exchange capacity, $\text{cmol}_c \text{ kg}^{-1}$	16.89†	16.05-17.73
Initial soil solution concentrations, $\text{mmol}_c \text{ L}^{-1}$		
Ca	20.465†	19.445-21.485
Mg	2.48†	2.36-2.6
Na	35.41†	33.64-37.18
K	0.22†	0.21-0.23
SO ₄	22.56†	21.435-23.685
Cl	19.16†	18.21-20.11
Applied water $\text{mmol}_c \text{ L}^{-1}$		
Ca	0.024†	-
Mg	0.0411†	-
Na	0.043†	-
K	0.048†	-
Alkalinity	0.005	-
SO ₄	0.00157†	-
Cl	0.006†	-
Precipitated Gypsum, meq Kg^{-1}	52.4†	32.4-72.4
Solution transport and reaction properties		
Bulk density, g cm^{-3}	1.2†	-
Diffusion coefficient, $\text{cm}^2 \text{ min}^{-1}$	0.001	0.001-0.025
Dispersivity, cm	1	0.1-4
Exchange coefficient $K_{\text{Ca/Na}}$	1.35†	1.1-1.5
Exchange coefficient $K_{\text{Ca/Mg}}$	0.51†	0.3-1
Exchange coefficient $K_{\text{Ca/K}}$	1.25†	1-1.5
Hydraulic properties		
Saturated hydraulic conductivity (K_s), cm min^{-1}	0.03†	-
Residual volumetric water content (θ_r)	0†	-
Saturated volumetric water content (θ_s)	0.48†	-
Inverse of the air entry suction α , $1/\text{cm}$	0.0139‡	-
Measure of the pore size distribution n	1.55‡	-
Pore connectivity parameter l	0.5‡	-
Discretization		
Grid spacing, cm	0.3	-
Initial time step, min	0.001	-
Min. time step, min	1×10^{-6}	-
Max. time step, min	1	-

† Measured properties using laboratory experiments

‡ Optimised properties using inverse modelling

Table 3. The HYDRUS model inputs for wood chips amended soil

Parameter	Value (base case)	Range for sensitivity analyses
Exchangeable cation concentration, $\text{cmol}_c \text{ kg}^{-1}$		
Ca	6.16†	5.86-6.46
Mg	4.68†	4.45-4.91
Na	18.66†	17.73-19.59
K	0.606†	0.57-0.63
Cation exchange capacity, $\text{cmol}_c \text{ kg}^{-1}$	30.10†	28.60-31.60
Initial soil solution concentrations, $\text{mmol}_c \text{ L}^{-1}$		
Ca	15.13†	14.375-15.885
Mg	4.085†	3.885-4.285
Na	31.68†	30.10-33.26
K	0.3†	0.29-0.31
SO ₄	22.8†	21.66-23.94
Cl	24.07†	22.87-25.27
Applied water $\text{mmol}_c \text{ L}^{-1}$		
Ca	0.024†	-
Mg	0.0411†	-
Na	0.043†	-
K	0.048†	-
Alkalinity	0.005	-
SO ₄	0.00157†	-
Cl	0.006†	-
Precipitated Gypsum, meq Kg^{-1}	49†	39-69
Solution transport and reaction properties		
Bulk density, g cm^{-3}	0.9†	-
Diffusion coefficient, $\text{cm}^2 \text{ min}^{-1}$	0.001	0.001-0.025
Dispersivity, cm	1	0.1-4
Exchange coefficient $K_{\text{Ca/Na}}$	1.06†	0.8-1.2
Exchange coefficient $K_{\text{Ca/Mg}}$	0.40†	0.3-1
Exchange coefficient $K_{\text{Ca/K}}$	0.79†	0.4-1
Hydraulic properties		
Saturated hydraulic conductivity (K_s), cm min^{-1}	0.07†	-
Residual volumetric water content (θ_r)	0†	-
Saturated volumetric water content (θ_s)	0.68†	-
Inverse of the air entry suction α , $1/\text{cm}$	0.02‡	-
Measure of the pore size distribution n	1.149‡	-
Pore connectivity parameter l	0.5‡	-
Discretization		
Grid spacing, cm	0.3	-
Initial time step, min	0.001	-
Min. time step, min	1×10^{-6}	-
Max. time step, min	1	-

† Measured properties using laboratory experiments

‡ Optimised properties using inverse modelling

Table 4. The HYDRUS model inputs for non-amended soil

Parameter	Value (base case)	Range for sensitivity analyses
Exchangeable cation concentration, $\text{cmol}_c \text{ kg}^{-1}$		
Ca	6.64†	6.31-6.97
Mg	6.37†	6.06-6.68
Na	16.94†	16.10-17.78
K	0.396†	0.38-0.40
Cation exchange capacity, $\text{cmol}_c \text{ kg}^{-1}$	30.34†	28.83-31.85
Initial soil solution concentrations, $\text{mmol}_c \text{ L}^{-1}$		
Ca	14.96†	14.215-15.705
Mg	6.67†	6.34-7
Na	63.29†	60.13-66.45
K	0.33†	0.32-0.34
SO ₄	32.76†	31.125-34.395
Cl	63.69†	60.51-66.87
Applied water $\text{mmol}_c \text{ L}^{-1}$		
Ca	0.024†	-
Mg	0.0411†	-
Na	0.043†	-
K	0.048†	-
Alkalinity	0.005	-
SO ₄	0.00157†	-
Cl	0.006†	-
Precipitated Gypsum, meq Kg^{-1}	66†	46-86
Solution transport and reaction properties		
Bulk density, g cm^{-3}	1.2†	-
Diffusion coefficient, $\text{cm}^2 \text{ min}^{-1}$	0.001	0.001-0.025
Dispersivity, cm	1	0.1-4
Exchange coefficient $K_{\text{Ca/Na}}$	2.43†	2-3.5
Exchange coefficient $K_{\text{Ca/Mg}}$	0.40†	0.2-0.9
Exchange coefficient $K_{\text{Ca/K}}$	1.08†	0.6-1.5
Hydraulic properties		
Saturated hydraulic conductivity (K_s), cm min^{-1}	0.01†	-
Residual volumetric water content (θ_r)	0†	-
Saturated volumetric water content (θ_s)	0.562†	-
Inverse of the air entry suction α , $1/\text{cm}$	0.035‡	-
Measure of the pore size distribution n	1.164‡	-
Pore connectivity parameter l	0.5‡	-
Discretization		
Grid spacing, cm	0.3	-
Initial time step, min	0.001	-
Min. time step, min	1×10^{-6}	-
Max. time step, min	1	-

† Measured properties using laboratory experiments

‡ Optimised properties using inverse modelling

Table 5. The results of statistical analyses for the agreement between the observed and predicted soil water potentials

K: results of statistical analysis when K_{red} function was not activated in the HYDRUS simulation; K_{red} : results of statistical analysis when K_{red} function was activated in the HYDRUS simulation; NSE: Nash-Sutcliffe co-efficient; d : index of agreement; RMSE: root mean square error; n: sample size as well as time series for the measured and simulated soil water potentials

Soil depth	Statistical analyses	Non-amended column		Wood chips amended column		Fine sand amended column	
		(n=9170)	(n=9170)	(n=9948)	(n=9948)	(n=10563)	(n=10563)
		K	K_{red}	K	K_{red}	K	K_{red}
35 mm	NSE	0.96	0.94	0.79	0.83	0.92	0.86
	d	0.99	0.98	0.96	0.97	0.98	0.97
	RMSE (kPa)	0.25	0.35	0.44	0.39	0.23	0.31
120 mm	NSE	0.94	0.96	0.97	0.93	0.98	0.95
	d	0.98	0.99	0.99	0.98	0.99	0.98
	RMSE (kPa)	0.27	0.21	0.16	0.27	0.11	0.17
250 mm	NSE	0.89	0.95	0.75	0.67	0.91	0.86
	d	0.97	0.98	0.91	0.89	0.97	0.95
	RMSE (kPa)	0.27	0.17	0.43	0.47	0.15	0.20

1 **Table 6. The results of statistical analyses for the agreement between the observed and predicted cations' concentrations, EC (Electrical**
2 **Conductivity) and SAR (Sodium Adsorption Ratio)**
3 K: results of statistical analysis when K_{red} function was not activated in the HYDRUS simulation; K_{red}: results of statistical analysis when K_{red}
4 function was activated in the HYDRUS simulation; RMSE: root mean square error; MAE: mean absolute error; RE: relative error (%); n: sample
5 size

Soil columns	Statistical analyses	EC	EC	SAR	SAR	Major cations (mmol/L)							
		(dS/m)	(dS/m)	(mmol _(c) L ⁻¹) ^{0.5}	(mmol _(c) L ⁻¹) ^{0.5}	Ca ²⁺	Ca ²⁺	Mg ²⁺	Mg ²⁺	Na ⁺	Na ⁺	K ⁺	K ⁺
		K	K _{red}	K	K _{red}	K	K _{red}	K	K _{red}	K	K _{red}	K	K _{red}
Non-amended column (n=3)	RMSE	0.73	0.76	1.97	2.00	0.99	0.99	0.329	0.37	7.61	7.91	0.07	0.07
	MAE	0.59	0.60	1.40	1.41	0.74	0.74	0.329	0.37	5.87	6.17	0.07	0.07
	RE	4.13	4.28	6.39	6.48	8.84	8.80	2.50	2.69	4.86	5.06	4.95	5.12
Fine sand amended column (n=3)	RMSE	0.84	0.83	1.38	1.33	0.19	0.19	1.19	0.86	6.22	5.87	0.102	0.07
	MAE	0.78	0.77	1.28	1.24	0.19	0.17	0.78	0.78	5.57	5.26	0.102	0.07
	RE	5.09	5.05	4.44	4.30	2.02	1.91	7.44	7.53	4.22	4.12	5.80	4.91
Wood chips amended column (n=3)	RMSE	0.65	0.61	0.97	0.91	0.22	0.19	1.11	1.02	6.09	5.43	0.05	0.05
	MAE	0.63	0.60	0.92	0.87	0.19	0.19	0.90	0.82	5.57	5.00	0.05	0.05
	RE	4.09	3.83	3.40	3.18	2.08	2.03	8.45	7.88	4.33	3.87	2.94	3.05

Table 7. Comparison of concentrations of ions (observed results) in the depth of 35 mm of the studied soil columns

Mean value $\pm$ standard deviation; EC_{1:5}: Electrical Conductivity of 1:5 soil solution extract; SAR: sodium adsorption ratio; * Significant at $P<0.05$; ns: non-significant ($P<0.05$); Within the same column, mean values followed by different letters differ significantly according to Duncan's test ($P<0.05$); n: sample size

Soil column	EC _{1:5} (dS/m) (n=3)	SAR (mmol L ⁻¹) ^{0.5} (n=3)	Na ⁺ (mmol/L) (n=3)	Ca ²⁺ (mmol/L) (n=3)	K ⁺ (mmol/L) (n=3)	Mg ²⁺ (mmol/L) (n=3)
Fine sand amended column	12.17 $\pm$ 0.14b	27.28 $\pm$ 1.2a	114.01 $\pm$ 5.22b	11.47 $\pm$ 0.19a	1.63 $\pm$ 0.02a	5.76 $\pm$ 0.41c
Wood chips amended column	11.94 $\pm$ 0.16b	22.22 $\pm$ 1.3b	102.69 $\pm$ 6.52b	11.225 $\pm$ 0.19a	2.17 $\pm$ 0.05a	9.87 $\pm$ 0.12b
Non-amended column	16.7 $\pm$ 0.25a*	29.1 $\pm$ 0.36a*	148.38 $\pm$ 0.43a*	11.97 $\pm$ 0.12a ^{ns}	1.73 $\pm$ 0.02a ^{ns}	13.5 $\pm$ 0.41a*

**Table 8. Comparison of concentrations of ions (observed results) in the depth of 120mm
of the studied soil columns**

Mean value $\pm$ standard deviation; EC_{1:5}: Electrical Conductivity of 1:5 soil solution extract; SAR: sodium adsorption ratio; ns: non-significant ($P < 0.05$); Within the same column, mean values followed by different letters differ significantly according to Duncan's test ($P < 0.05$); n: sample size

Soil column	EC _{1:5} (dS/m) (n=3)	SAR (mmol L ⁻¹) ^{0.5} (n=3)	Na ⁺ (mmol/L) (n=3)	Ca ²⁺ (mmol/L) (n=3)	K ⁺ (mmol/L) (n=3)	Mg ²⁺ (mmol/L) (n=3)
Fine sand amended column	19.16 $\pm$ 0.2a ^{ns}	33.11 $\pm$ 0.58a	167.53 $\pm$ 2.61 a	10.72 $\pm$ 0.12a	1.94 $\pm$ 0.07a	14.4 $\pm$ 0.41a
Wood chips amended column	19.03 $\pm$ 0.3a	33.95 $\pm$ 1.3a ^{ns}	171.45 $\pm$ 6.96 a ^{ns}	10.47 $\pm$ 0.09a	1.96 $\pm$ 0.05a	14.81 $\pm$ 0.32a
Non-amended column	18.76 $\pm$ 0.25a	32.07 $\pm$ 0.55a	164.49 $\pm$ 2.17 a	11.29 $\pm$ 0.17a ^{ns}	1.94 $\pm$ 0.05a ^{ns}	14.81 $\pm$ 0.20a ^{ns}

**Table 9. Comparison of concentrations of ions (observed results) in the depth of 250 mm
of the studied soil columns**

Mean value $\pm$ standard deviation; EC_{1:5}: Electrical Conductivity of 1:5 soil solution extract; SAR: sodium adsorption ratio; ns: non-significant ($P < 0.05$); Within the same column, mean values followed by different letters differ significantly according to Duncan's test ($P < 0.05$); n: sample size

Soil column	EC _{1:5} (dS/m) (n=3)	SAR (mmol L ⁻¹) ^{0.5} (n=3)	Na ⁺ (mmol/L) (n=3)	Ca ²⁺ (mmol/L) (n=3)	K ⁺ (mmol/L) (n=3)	Mg ²⁺ (mmol/L) (n=3)
Fine sand amended column	18.43 $\pm$ 0.15a ^{ns}	33.23 $\pm$ 0.35a ^{ns}	164.05 $\pm$ 2.17a ^{ns}	10.72 $\pm$ 0.04a	1.94 $\pm$ 0.05a	13.58 $\pm$ 0.32a
Wood chips amended column	18.03 $\pm$ 0.47a	32.13 $\pm$ 0.47a	162.31 $\pm$ 3.91a	10.23 $\pm$ 0.09a	1.94 $\pm$ 0.02a	15.22 $\pm$ 0.41a ^{ns}
Non-amended column	18.36 $\pm$ 0.23a	30.53 $\pm$ 0.86a	154.91 $\pm$ 0.07a	10.72 $\pm$ 0.09a ^{ns}	1.86 $\pm$ 0.02a ^{ns}	14.81 $\pm$ 0.20a